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Performance of conventional operational forecasts of clear-air turbulence during the 1976 Turbulence Survey

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Summary

During the 1976 Turbulence Survey the pilots' reports of clear-air turbulence (CAT) from about 4500 flights over the North Atlantic and north-west Europe were collected. In addition to a continuing investigation into the relationship between reports of CAT and synoptic-scale meteorological variables computed by the operational 10-level model, an assessment has been made of the skill of conventional forecasts of CAT prepared in the Central Forecasting Office (CFO) during the survey; that assessment is presented here. The results indicate that the CFO forecasts showed some (significant) skill in discriminating between regions more prone than average and those less prone than average to moderate or severe CAT. The frequency of encounter, per unit distance flown, with moderate or severe CAT within regions forecast to contain moderate or severe CAT was about double the frequency of encounter outside these regions.

1. Introduction

Following the earlier 1972 Turbulence Survey (Sparks *et al.*, 1977) a much more extensive survey, organized by the Meteorological Office, was carried out during the spring of 1976, with the co-operation of the meteorological services and airlines of Austria, Belgium, Denmark, Federal Republic of Germany, France, Republic of Ireland, Italy, The Netherlands, Norway, Spain, Sweden, Switzerland and U.S.A. On ten pre-selected reporting days (9, 12, 15, 18, 21, 24, 27, 30 March and 2, 5 April) spaced at regular 3-day intervals during spring 1976, pilots were issued with specially printed maps covering the North Atlantic (Figure A1 in Appendix) and north-western Europe (Figure A2 in Appendix), and asked to record on them complete turbulence histories of their flights (cruise phase only). Information about the survey and an example of the type of report required were printed on the back of each map (Figure A3 in Appendix).

Pilots' response was quite good; a total of 4378 usable maps were received (3·9 million kilometres of flight) of which 3805 (2·1 million km) were 'EUROPEAN' and 573 (1·8 million km) 'ATLANTIC'. Digitizing and quality control of the reports proved a lengthy task. The clean data have been stored on magnetic tape for analysis; this will include comparison of pilots' (mainly subjective) reports with forecasts of synoptic-scale meteorological indices produced by the operational 10-level numerical

model (Burridge and Gadd, 1977). Some basic statistics of the reports themselves are shown in Tables A1, A2 and A3 of the Appendix to this note; overall, 0·013 per cent of flight distance was reported as severely turbulent (only eight reports in all), 1·26 per cent as at least moderately turbulent while 9·92 per cent of distance was flown in at least light turbulence. These figures relate specifically to turbulence in clear air (clear-air turbulence, usually referred to as CAT).

Figures 1(a) to 1(d) show the 12 GMT 300-mb contour charts, with surface fronts indicated, for four of the ten reporting days; areas of forecast CAT (verifying time 12 GMT) are indicated and locations of encounters with moderate and moderate to severe CAT and severe CAT are superimposed. Only those encounters within the time period 03–21 GMT each day are included. The pecked lines enclose areas for which *at least ten* aircraft submitted full reports and therefore highlight the areas of densest air traffic.

The main object of the survey and subsequent analysis is to develop an operational scheme for objectively deriving forecast probabilities (per unit distance flown) of encountering moderate or severe clear-air turbulence, using the 10-level numerical model. A composite index will be derived including the most relevant synoptic-scale meteorological variables, such as wind shear (horizontal and vertical), vertical motion, rate of change of (100-mb layer) Richardson number, etc. (as computed by the numerical model). Multiple linear regression and discriminant analysis techniques will be used to derive this empirical CAT index; any given value of the index will imply a given probability, per unit distance of flight (for example 100 km), of encountering moderate or severe CAT.

This project includes an assessment of conventional forecasts of CAT, prepared in the Central Forecasting Office (CFO), occasionally amended at Heathrow's Forecast Office and issued to aircrew at Heathrow during the 1976 survey. The results of this assessment are presented in this note; they confirm the previously purely intuitive feeling that such forecasts show comparatively low skill; in addition they give no indication of the probability of encountering CAT.

The individual performance of each of several meteorological variables as predictors of CAT is currently in progress, along the lines followed in the analysis of pilots' reports from the 1972 survey.

The view, expressed in the report on the 1972 survey, that CAT forecasts must be stated in terms of probability if they are to convey the maximum possible information to the recipient, is still held. That report also tentatively concluded that 'forecasts produced by the 10-level model contain information which allows positive predictions of bumpiness which are about as good as those based on recent pilots' reports'.

2. CFO forecasts of CAT and pilots' experience

(a) *The CFO forecasts.* For each of the ten reporting days the CAT forecasts, prepared in CFO in chart form and issued to aircrew at Heathrow, were assessed by comparing pilots' reported experience with the relevant forecasts. The 'EUMED' (covering north-west Europe and the western Mediterranean) and 'N ATLANTIC' forecast significant-weather charts for verification times 06, 12 and 18 GMT, on each day, were digitized on a grid-square (100 km × 100 km) basis (the grid squares corresponding to those of the rectangle (fine-mesh) area of the 10-level model) by assigning, as appropriate, 'MODERATE CAT' or 'MODERATE OCCASIONALLY SEVERE CAT'* to each grid-square or level lying within regions forecast to be turbulent (see Figure 2 for symbols and abbreviations used in this context). All other grid-squares or levels were, by default, assigned 'NIL CAT'. The 'EUMED' chart was used for areas east of 10°W, while the 'N ATLANTIC' chart was used for areas west of 10°W.

* 'MODERATE LOCALLY SEVERE CAT' was much less frequently used.

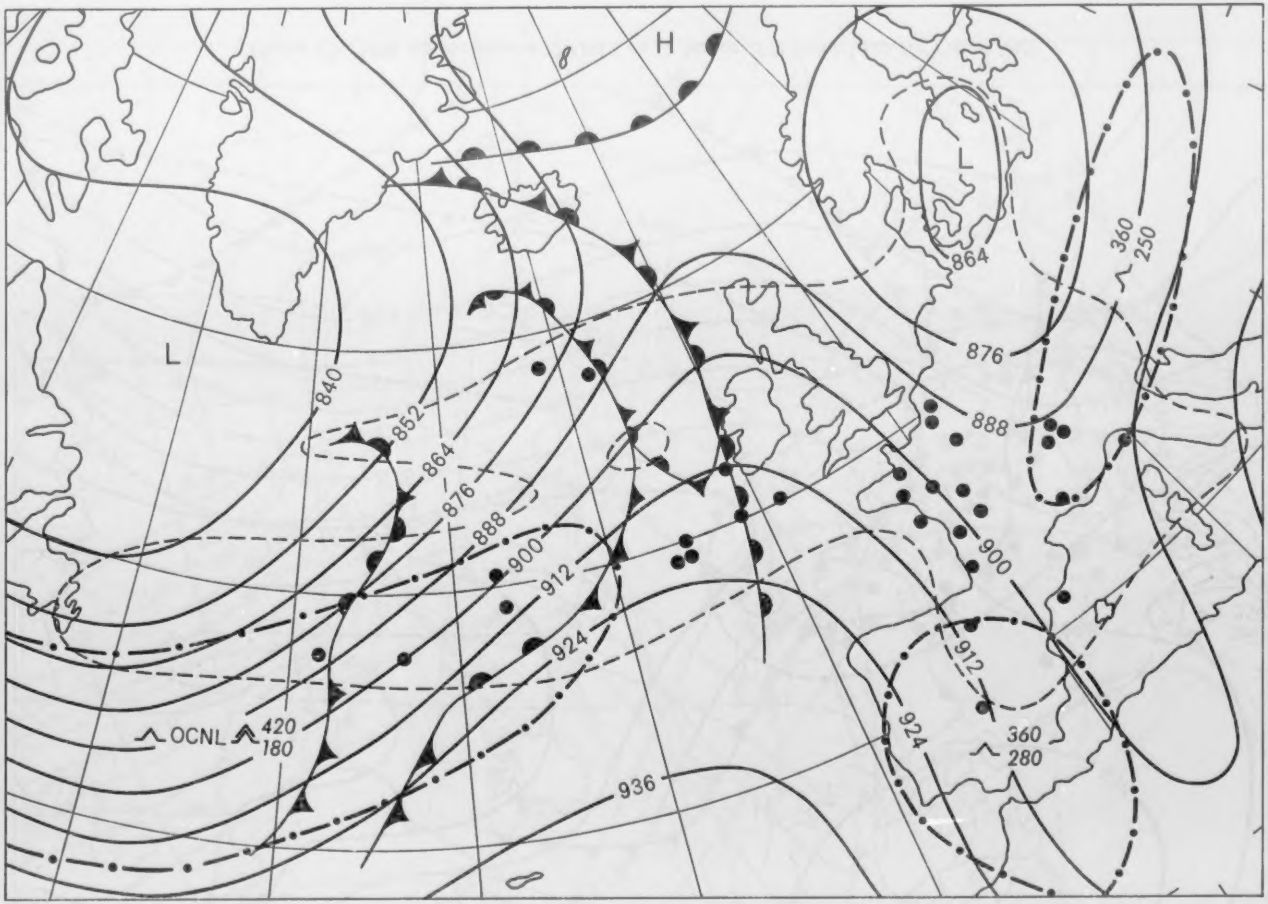

Figure 1(a). 300 mb contours at 12 GMT on 9 March 1976
Heights are in decageopotential metres. Surface fronts are indicated. Locations of encounters with moderate and moderate to severe CAT are indicated by black dots and those of encounters with severe CAT by encircled black dots. Areas of forecast CAT (verifying time 12 GMT) are indicated by symbols explained in Figure 2; the adjacent figures represent flight levels in hundreds of feet. Pecked lines encircle areas for which *at least ten* aircraft submitted full reports and therefore highlight the areas of densest air traffic.

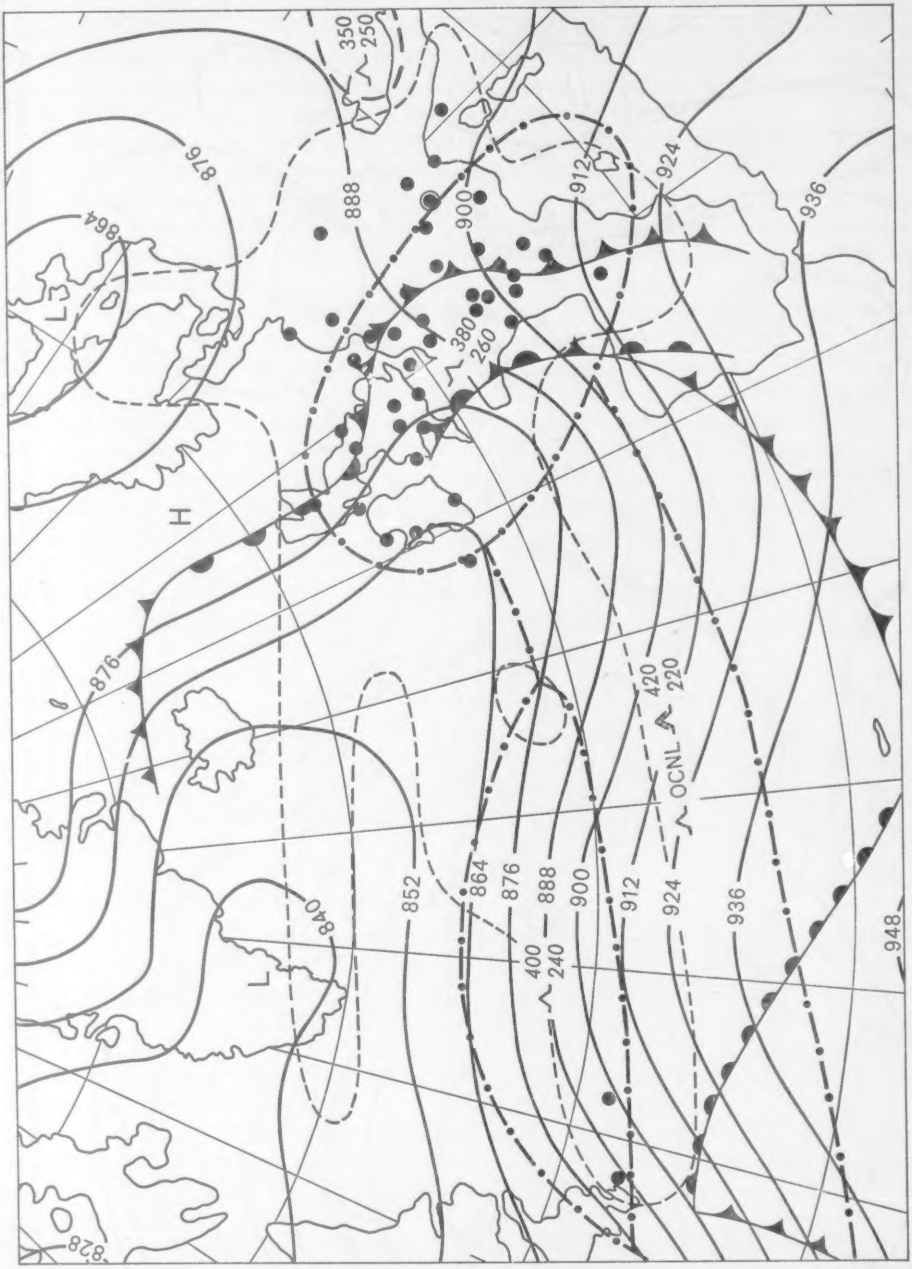

Figure 1(b). 300 mb contours at 12 GMT on 12 March 1976 (remarks as for Figure 1(a))

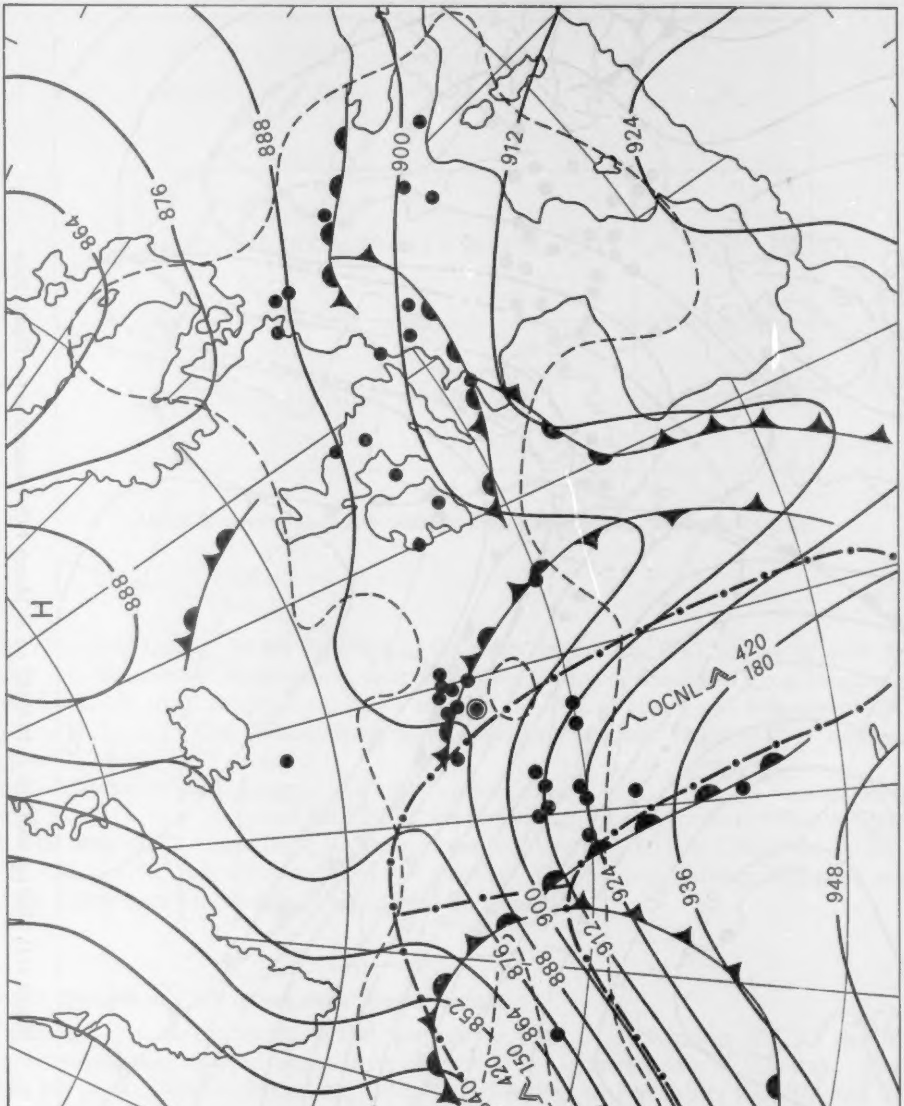

Figure 1(c). 300 mb contours at 12 GMT on 18 March 1976 (remarks as for Figure 1(a))

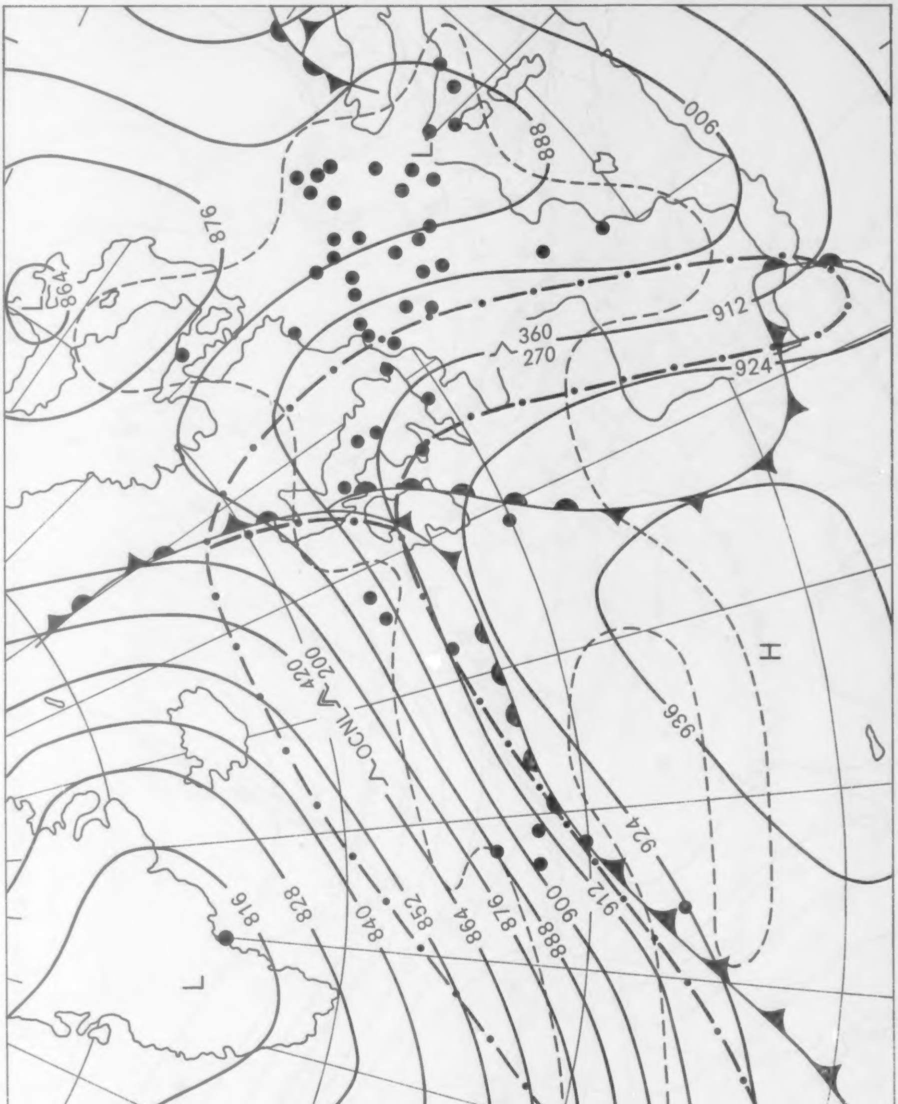

Figure 1(d). 300 mb contours at 12 GMT on 24 March 1976 (remarks as for Figure 1(a))

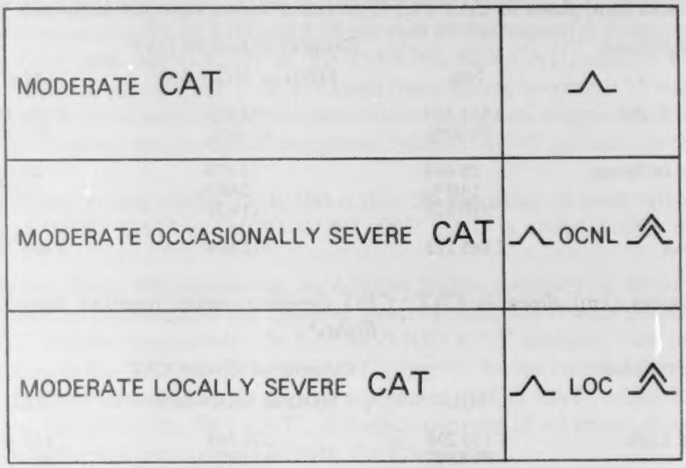

Figure 2. Symbols and abbreviations used for indicating the severity of CAT

(b) *The pilots' reports.* In the digitizing of the pilots' reports the CAT history of each flight was divided into 'elementary' observations; each elementary observation included the grid-square (10-level model fine-mesh area), height, time, length of track in the grid-square and intensity of CAT along that length of track. This format allows easy comparison of pilots' reported CAT experience with computed 10-level model variables.

(c) *Comparison of CAT forecasts and pilots' reports.* The CAT forecasts for verification times 06, 12 and 18 GMT were compared with pilots' reports within the time periods 0300–0859, 0900–1459 and 1500–2059 GMT respectively, for each of the ten reporting days; a total of 30 'EUMED' and 30 'N ATLANTIC' forecasts were therefore assessed. Comparisons between European and North Atlantic flights were analysed, both separately and combined.

3. CFO forecasts of CAT versus pilots' reports: results

Tables I(a–c) show the results of the comparisons between the forecasts of CAT and the pilots' reported experience. A brief explanation of these tables is appropriate at this stage. Each set of results (all flights, Atlantic flights, European flights) is presented in Tables I(a), I(b) and I(c). Note that 'MODERATE' and 'MODERATE OCCASIONALLY SEVERE' forecast categories are combined into a single category, while the pilot-report categories are also reduced to two, 'Nil or Light' and 'Moderate or Severe'. Each table gives the total distances flown in each category, and the associated percentages of the total distances flown within the regions designated by the various categories of forecast CAT. For instance, in Table I(a), 811 604 km was flown within regions designated 'MOD CAT' or 'MOD OCNL SEV CAT'; 794 925 km, or 97·94 per cent, of this was reported as containing 'NIL' or 'LIGHT' CAT, while the remainder, 16 679 km or 2·06 per cent, was

Table I(a). *Distances* (km) *flown in* CAT : CFO *forecasts versus reported bumpiness for all flights**

Pilots' experience	Category of forecast CAT		
	NIL	MOD or MOD–SEV	ALL
Nil or Light	2 835 510 98·97%	794 925 97·94%	3 630 435 98·74%
Moderate or Severe	29 614 1·03% (0·82)	16 679 2·06% (1·63)	46 293 1·26%
All	2 865 124	811 604	3 676 728

Table I(b). *Distances* (km) *flown in* CAT : CFO *forecasts versus reported bumpiness for Atlantic flights**

Pilots' experience	Category of forecast CAT		
	NIL	MOD or MOD–SEV	ALL
Nil or Light	1 110 298 99·68%	534 863 97·83%	1 645 161 98·40%
Moderate or Severe	14 868 1·32% (0·83)	11 889 2·17% (1·36)	26 757 1·60%
All	1 125 166	546 752	1 671 918

Table I(c). *Distances* (km) *flown in* CAT : CFO *forecasts versus reported bumpiness for European flights**

Pilots' experience	Category of forecast CAT		
	NIL	MOD or MOD–SEV	ALL
Nil or Light	1 725 212 99·15%	260 062 98·19%	1 985 274 99·03%
Moderate or Severe	14 746 0·85% (0·88)	4 790 1·81% (1·87)	19 536 0·97%
All	1 739 958	264 852	2 004 810

* In Tables I(a–c) total distances (km) flown in each category are given; below each distance the percentage of the distance flown within that forecast category is given; figures in parentheses are the ratios of these percentages to the overall (background) percentages (see text).

reported to be at least moderately turbulent. In regions with 'NIL CAT' forecast* on the other hand, 98·97 per cent of flight distance was reported to contain 'NIL' or 'LIGHT' CAT, and 1·03 per cent was reported to be moderately turbulent.

The figures in parentheses are the ratios of the given percentages to the overall (background) percentage, given in the right-hand column under 'ALL'; for instance, in Table I(a) again, 1·03 per cent represents 0·82 of the overall frequency of encounter with at least moderate CAT (1·26 per cent, as given in the right-hand column), while 2·06 per cent is 1·63 times this background frequency.

* Throughout this note, the 'NIL CAT' forecast category is simply used as the default category; it is never the intention of the forecast to imply that areas outside those designated as being particularly prone to CAT will be entirely free from CAT.

(a) *Results for all flights combined.* Table I(a) shows that, grouping all flights together, moderate or severe CAT was experienced over 1·03 and 2·06 per cent of the respective distances flown in regions designated 'NIL CAT' and 'MOD CAT' or 'MOD OCNL SEV CAT'; relative to the background frequency of moderate or severe CAT (1·26 per cent) these figures become 0·82 and 1·63. Note that 63 per cent of all moderate or severe CAT was encountered in regions designated 'NIL CAT'. Overall, 22 per cent of flight distance was in regions designated 'MOD CAT' (8 per cent) or 'MOD OCNL SEV CAT' (14 per cent).

The main conclusion arising out of Table I(a) is that the frequency of moderate or severe CAT in regions designated 'MOD CAT' or 'MOD OCNL SEV CAT' is about double that in regions of 'NIL CAT'.

(b) *Atlantic flights.* Table I(b) shows that, on Atlantic flights, moderate or severe CAT was experienced over 1·32 and 2·17 per cent of the distance flown in 'NIL CAT' and 'MOD CAT' or 'MOD OCNL SEV CAT' regions respectively. In fact the 'MOD CAT' category was used comparatively infrequently, relative to the 'MOD OCNL SEV CAT' category, on the North Atlantic forecast charts; 7·5 per cent of all flight distance was in regions designated 'MOD CAT', while 25 per cent was in regions designated 'MOD OCNL SEV CAT'. Fifty-five per cent of all reported moderate or severe CAT on Atlantic flights was encountered in 'NIL CAT' regions.

(c) *European flights.* Table I(c) shows that, on European flights, moderate or severe CAT was encountered over 0·85 and 1·81 per cent of the distance flown in 'NIL CAT' and 'MOD CAT' or 'MOD OCNL SEV CAT' regions respectively.

Overall, 13 per cent of flight distance was in regions designated 'MOD CAT' (9 per cent) or 'MOD OCNL SEV CAT' (4 per cent). Seventy-five per cent of all reported moderate or severe CAT on European flights was encountered in 'NIL CAT' regions.

The figures presented so far tell us what *proportion* of distance flown fell into various categories; for example, in regions of 'NIL CAT' the proportion of distance flown in moderate or severe CAT was 1·03 per cent. To get an idea of the probability per unit flight distance (say 100 km or 1000 km) of an encounter with moderate or severe CAT we need to approach the problem slightly differently.

One approach is first to re-format the pilots' reports by defining a pilot's CAT experience of any single 100 km $\times$ 100 km grid-square as equivalent to the most severe CAT encountered within that grid-square. In this way, if a pilot encounters moderate CAT anywhere within a grid-square, albeit for only a few kilometres, his CAT experience of that grid-square would be classified as 'moderate'. If this procedure is followed for all pilots' reports then the pilots' grid-square experiences (so-called 'elementary' grid-square reports) can readily be compared with the CAT forecasts (or computed 10-level model meteorological indices) for the corresponding grid-squares.

On the basis of this alternative method of analysis, contingency tables, similar to those already presented, can be constructed giving the number of these elementary reports falling into the various categories (Table II(a–c)). The percentages in these tables now approximate to the percentage probabilities of encountering CAT per traversed grid-square; these figures will provide a standard against which to compare the performance, as CAT predictors, of various meteorological indices forecast by the 10-level model.

As expected the results in Tables II(a–c) confirm the main conclusion arising out of Tables I(a–c), namely that the probability of encountering moderate or severe CAT in 'MOD CAT' or 'MOD OCNL SEV CAT' forecast regions is about double that in 'NIL CAT' regions; it is not necessary here to describe the results in Tables II(a–c) in any detail.

Chi-square tests indicate that the apparent degree of skill, albeit rather low, in forecasting areas of CAT (moderate or severe) or NIL CAT is highly significant, well beyond the 0·01 per cent level, for

Table II(a). *Elementary observations of* CAT : CFO *forecasts versus reported bumpiness for all flights**

Pilots' experience	Category of forecast CAT		
	NIL	MOD or MOD–SEV	ALL
Nil or Light	39 630 98·62%	10 317 97·17%	49 947 98·32%
Moderate or Severe	555 1·38% (0·82)	300 2·83% (1·68)	855 1·68%
All	40 185	10 617	50 802

Table II(b). *Elementary observations of* CAT : CFO *forecasts versus reported bumpiness for Atlantic flights**

Pilots' experience	Category of forecast CAT		
	NIL	MOD or MOD–SEV	ALL
Nil or Light	13 773 98·20%	6 475 97·13%	20 248 97·85%
Moderate or Severe	253 1·80% (0·84)	191 2·87% (1·33)	444 2·15%
All	14 026	6 666	20 692

Table II(c). *Elementary observations of* CAT : CFO *forecasts versus reported bumpiness for European flights**

Pilots' experience	Category of forecast CAT		
	NIL	MOD or MOD–SEV	ALL
Nil or Light	25 857 98·85%	3 842 97·24%	29 699 98·64%
Moderate or Severe	302 1·15% (0·85)	109 2·76% (2·03)	411 1·36%
All	26 159	3 951	30 110

* In Tables II(a–c) the numbers of 'elementary' (grid-square) reports in each category are given; below each number is the percentage of these 'elementary' reports within areas designated by the forecast category; figures in parentheses are the ratios of these percentages to the overall (background) percentages (see text).

both Atlantic and European flights. However, it should be pointed out that strict validity of such tests is conditional on the assumptions of random sampling and normal distribution of the variables. The data presented here satisfy neither condition since:

(1) the definition of the 'elementary' grid-square observations often results in the same (continuous) patch of CAT being counted as two or more 'elementary' observations, one for each grid-square traversed within the patch, and

(2) areas of forecast CAT occupy specific synoptic-scale regions; 100 km × 100 km (mesoscale) grid-square categories of forecast CAT therefore obviously exhibit considerable spatial coherence, so that the categories for adjacent grid-squares are significantly correlated. This argument also applies, although to a lesser extent, to the actual reports of CAT, since turbulent patches often occur in conglomerates that have synoptic scale.

Sparks *et al.* (1976) have shown that, subject to certain simplifying assumptions, if the mean probability of encountering a given event (for example, moderate turbulence) in a grid-square (100 km × 100 km), P_s, is known, then the probability of encountering such an event in 100 km of linear flight, under the same conditions, can be calculated; for $P_s < 0{\cdot}2$, $P_{100} = 1{\cdot}24\,P_s$. Given P_s or P_{100}, it is possible to estimate the probabilities for greater flight distance; for example, if $n \times 100$ km of flight-path traverses a region in which P_{100} is approximately constant (and known) then

$$P_{n\times100} = 1 - (1 - P_{100})^n.$$

Table III gives overall probabilities of encountering moderate or severe CAT over flight distance *L*, in, on the one hand, 'NIL CAT' regions and, on the other hand, 'MOD CAT' or 'MOD OCNL SEV CAT' regions, using the basic P_s (probability per grid-square) figures in Table II(a), and assuming that P_s is constant over the distance *L*.

Table III. *Probabilities of encountering moderate or severe* CAT *over flight distance L, assuming that P_s is constant*

	$L = 100$ km	$L = 500$ km	$L = 1000$ km	$L = 2000$ km
		Per cent		
'NIL CAT' regions ($P_s = 1{\cdot}38$ per cent)	1·7	8·3	15·8	29·2
'MOD CAT' or 'MOD OCNL SEV CAT' regions ($P_s = 2{\cdot}83$ per cent)	3·5	16·4	30·0	51·1

4. Concluding remarks

The analysis of data collected during the 1976 survey is continuing. If the promising results arising out of the analysis of the 1972 survey are confirmed by the much more extensive 1976 data set, then it is highly likely that probability forecasts of clear-air turbulence, derived entirely from 10-level model fields, can be introduced on an operational basis at some time during 1979. Of the individual synoptic-scale meteorological indices, forecast by the numerical model and so far tested as predictors of moderate or severe CAT, it appears that vertical and horizontal wind shear perform significantly better than most other indices such as vertical velocity, deformation, vorticity, Richardson number and rate of change of Richardson number (following the flow). Indeed, preliminary results indicate that both vertical and horizontal wind shear, considered separately, performed as well as, or slightly better than, the CFO forecasts assessed in this note. It is therefore confidently expected that forecasts of CAT based on a composite index incorporating the predictive ability of several indices, will perform markedly better than current CFO forecasts.

Typically, on the form of forecast chart currently envisaged, the highest probabilities of moderate or severe CAT (per 100 km of flight) indicated would be about 15–20 per cent, and regions with this level of probability (or greater) would typically cover about 1 per cent of total chart area; regions with a forecast CAT probability of 10 per cent or more would on average be expected to cover about 5 per cent of chart area.

It is felt that such forecasts will prove more reliable and useful to airlines and pilots than those prepared using current methods; they may be particularly useful for flight-planning purposes when a choice of routes is possible (across the Atlantic for example), since overall route-probabilities can easily be calculated from the readily available grid-square values of P_{100} (probability per 100 km of flight).

The main purpose of this note has been to give some quantitative feel for the skill of current clear-air turbulence forecasts prepared in CFO, by comparing 30 such forecasts, covering north-west Europe and the North Atlantic, with pilots' reported CAT experience. The results have shown that the proportion of distance flown in moderate or severe CAT in areas of 'NIL CAT' (1·03 per cent—about 0·8 of the background frequency) was half that in areas designated 'MOD CAT' or 'MOD OCNL SEV CAT' (2·06 per cent—about 1·6 times the background frequency).

Acknowledgements

Thanks are due to all the national meteorological services and airlines, most particularly their pilots, who co-operated to make a success of the 1976 Turbulence Survey, on which the results of this note are based.

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Sparks, W. R., Cornford, S. G. and Gibson, J. K. 1976 A report of the 1972 Clear-Air Turbulence Survey. (Unpublished, copy available in Meteorological Office Library, Bracknell.)

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APPENDIX

Table A1. *Percentages of distance flown in clear-air turbulence—all flights*

Flight level	Reported CAT Light+	Moderate+	Severe+	Total distance flown (km)
<100	9·17	1·09*	0·242*	13 245
100–149	8·29	0·44*	0·077*	38 816
150–199	8·29	0·53	0·061*	111 895
200–249	9·19	0·67	0·018*	236 872
250–299	10·72	1·43	0·006*	686 695
300–349	8·87	0·90	0·012*	1 385 671
350–399	10·92	1·72	0·005*	1 415 676
⩾400	5·30	0·24*	0·236*	16 557
All	9·92	1·26	0·013	3 905 427

Table A2. *Percentages of distance flown in clear-air turbulence—European flights*

Flight level	Reported CAT Light+	Moderate+	Severe+	Total distance flown (km)
<100	9·17	1·09*	0·242*	13 245
100–149	8·29	0·44*	0·077*	38 816
150–199	8·51	0·55	0·062*	108 970
200–249	9·31	0·70	0·019*	229 460
250–299	11·25	1·46	0·007*	644 742
300–349	9·73	0·61	—	744 909
350–399	10·82	1·25	—	317 504
⩾400	6·01*	0·72*	0·717*	5 441
All	10·21	0·97	0·012	2 103 087

Table A3. *Percentages of distance flown in clear-air turbulence—Atlantic flights*

Flight level	Reported CAT Light+	Moderate+	Severe+	Total distance flown (km)
<100	—	—	—	0
100–149	—	—	—	0
150–199	—	—	—	2 925
200–249	5·48*	—	—	7 412
250–299	2·48	0·91*	—	41 953
300–349	7·88	1·22	0·027*	640 762
350–399	10·94	1·86	0·006*	1 098 172
⩾400	4·96*	—	—	11 116
All	9·58	1·59	0·013*	1 802 340

* Denotes that the percentage is based on fewer than 5 encounters with CAT. Flight levels are expressed in hundreds of feet.

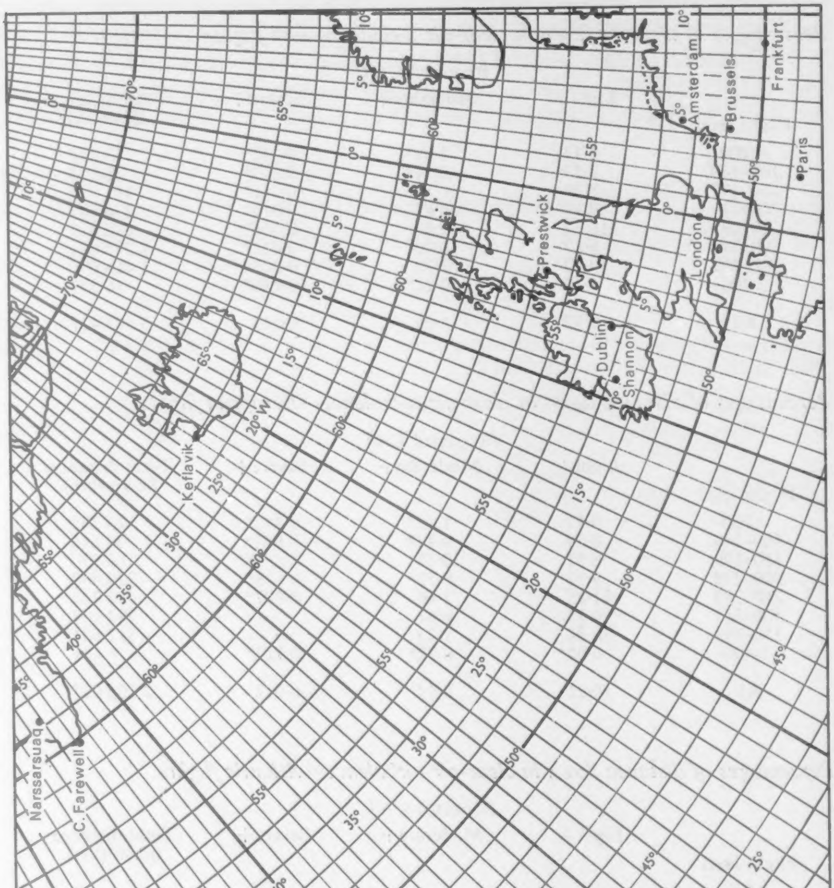


Figure A1. Turbulence Survey (1976) reporting map—ATLANTIC flights

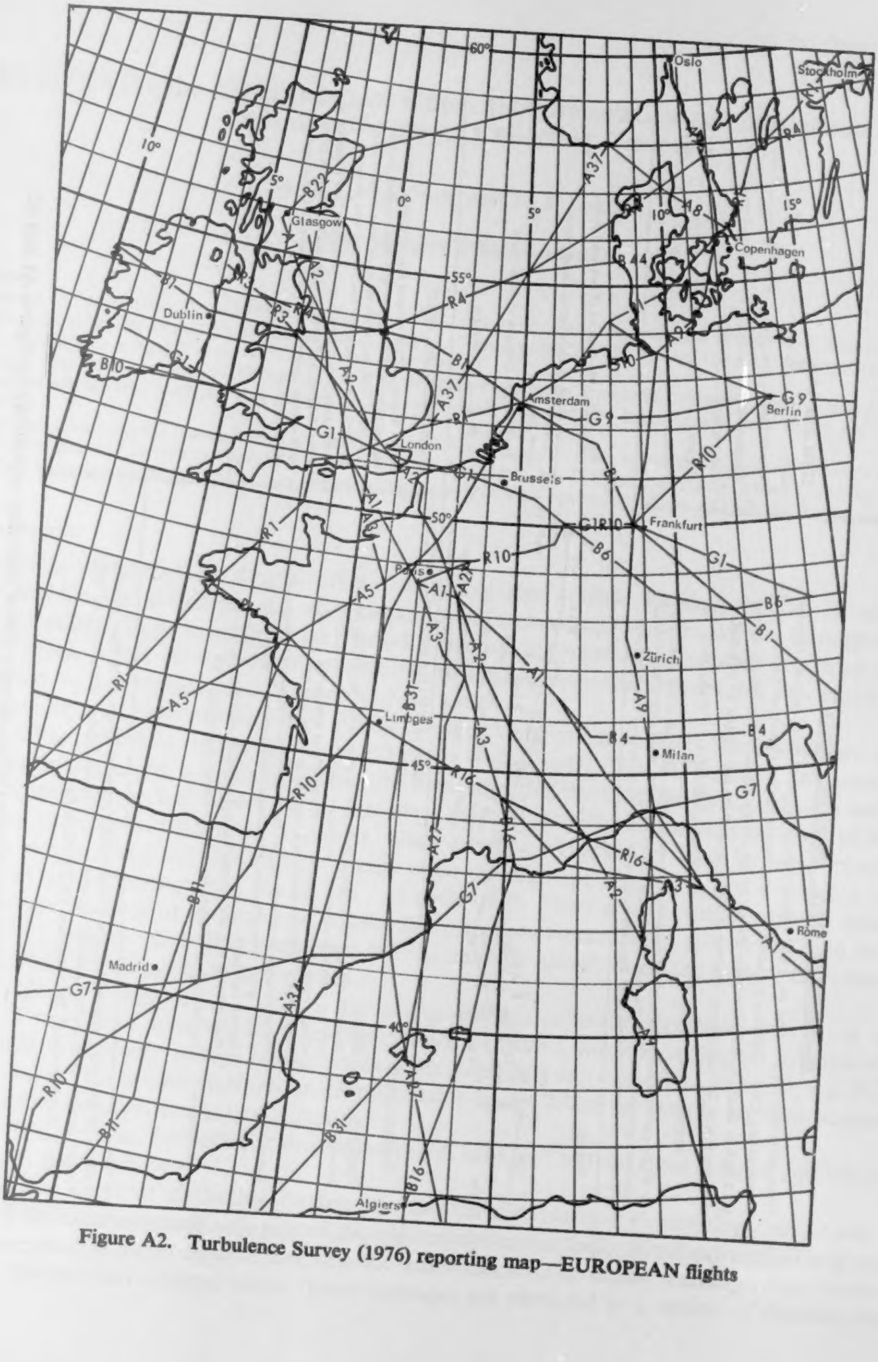


Figure A2. Turbulence Survey (1976) reporting map—EUROPEAN flights

METEOROLOGICAL OFFICE TURBULENCE SURVEY

These maps are being issued on a few chosen days in order to help assess techniques of forecasting CAT. Captains are asked to complete the flight information section on the right and to describe the turbulence history of the cruise stage of their flight on the map overleaf. All turbulence, whether in cloud or in clear air, should be reported.

REPORTS OF NO TURBULENCE ARE AS IMPORTANT AS REPORTS OF TURBULENCE

For all points of the cruise stage within the area of the map indicate the track, flight level, and turbulence encountered. Mark the time (GMT) at convenient intervals. When LIGHT, MODERATE, or SEVERE turbulence is encountered show any cloud in the vicinity as in the example below.

Flight information

Date ....

Aircraft type ....

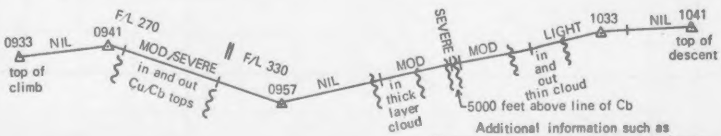
Company/Unit ....

Flight number ....

Departed .... at .... GMT

Arrived .... at .... GMT

Example



Additional information such as wind measurements would be most welcome

Key

NIL MOD Boundaries of turbulent zones

in thick layer cloud Boundaries of cloudy zones

F/L 270 || F/L 290 Changes of flight level

Time mark

Turbulence criteria

(Based on ICAO Doc.8812, AN-CONF/6, 1969)

Description	Effects
Moderate	Moderate changes in aircraft attitude and/or altitude but the aircraft remains in positive control at all times. Variations in air speed are usually small. Loose objects move about. Occupants feel strain against seat belts. Peak changes in accelerometer readings at c.g. of 0.5 g to 1.0 g.
Severe	Abrupt changes in aircraft attitude and/or altitude. Variations in airspeed are usually large. Loose objects tossed about. Occupants are forced violently against seat belts. Peak changes in accelerometer readings at c.g. of more than 1.0 g.
Light/extreme	may be reported when effects are less/greater than these.

The reasons for this survey

A CAT survey in 1972 showed that a report of CAT from another pilot within one hour was more reliable than a forecast of CAT, but when the other pilot's report was more than three hours old the forecast was better.

The objects of this survey are to improve CAT forecasts and to find ways of combining recent reports from pilots with meteorological forecasts to make CAT warnings more reliable

Captains are asked to hand maps to a British meteorological office or to their company representative at their destination to be sent to The Director-General, Meteorological Office (Met O 9), London Road, Bracknell, Berks RG12 2SZ, U.K.

Figure A3. Turbulence Survey (1976)—Reverse side of reporting maps shown in Figures A1 and A2

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AUTOPREP—the Meteorological Office data preparation and telecommunication terminal for use at Collecting Centres

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Summary

In order to ensure smooth and rapid operation of the automated telecommunication system now installed at HQ, Meteorological Office, Bracknell, meteorological messages being passed to the system from Collecting Centres must conform rigidly to a standard uniform layout or protocol.

Several Main Meteorological Offices as well as sending reports to Bracknell transmit meteorological data to external organizations, such as Regional Gas Boards, which also require high-quality data input for computer processing.

These requirements, for the maintenance of strict discipline in regard to the telecommunication format of meteorological messages, will be met in the near future with the assistance of AUTOPREP terminals which are to be installed at major Collecting Centres. This paper describes the principles and operation of the AUTOPREP system.

1. Introduction

The Telecommunications Centre of the Meteorological Office Headquarters at Bracknell is responsible for the collection and dissemination of meteorological information throughout the United Kingdom. These operations are effected through a computer-based message switching system, (AUTOCOM), which also provides connections to an international network for the exchange of information with other Centres in Europe and the U.S.A.

The handling of telecommunication traffic at the Meteorological Telecommunications Centre (Met. T.C.) is carried out automatically at extremely high speeds. The AUTOCOM computers use, for message distribution, a routeing system which requires the identification details of each meteorological message to be free of errors, so that they match precisely the message heading contained within the routeing list held in the computer. Each message is checked in detail by the computer on receipt, and any which fail this check are sent to an operator for inspection and correction before re-insertion of the message into the system. At peak traffic hours a high rate of rejected messages can cause the operator to be unable to handle all corrections immediately, with a resulting slowing up of the operations. It is thus important for the smooth operation of the system to reduce the number of rejected messages to a minimum.

In the United Kingdom 12 Regional Collecting Centres collect observations which are made regularly at more than 240 stations. These reports are assembled into meteorological bulletins which by the addition of special groups of characters at the beginning and end of the bulletins, e.g. ZCZC, NNNN, etc., are made ultimately into meteorological messages which are then in the form acceptable to the Bracknell telecommunication computers.

AUTOPREP terminals installed at these Centres will help staff to fulfil these detailed and laborious tasks quickly and accurately.

Most of the Regional Collecting Centres are located at Principal Forecasting Offices and the handling of the observations is only part of the telecommunication task. Much extra effort is involved in the preparation of paper tapes to facilitate the transmission of forecasts, warnings, reports, etc. to subsidiary stations and external users. These messages are prepared in a variety of formats, many

of which contain a large proportion of fixed data. The AUTOPREP equipment is intended to aid the preparation of these messages and at some Centres will include an autodial telex to simplify message transmissions.

As a result of a prolonged tendering exercise a contract for 12 AUTOPREP terminals was placed at the beginning of 1978. The first unit of production is expected at HQ, Meteorological Office, Bracknell early in 1979, followed by a further 11 sets of equipment during the following six months.

2. Requirement

The features specified to meet the requirement were as follows:

(a) Visual Display Unit (VDU) with at least 24 lines of 69 characters, a standard 'QWERTY' type keyboard and a separate function key layout to control frequently used system functions such as 'SEND', 'CLEAR SCREEN', etc.

Dedicated keys to provide for the fast movement of the cursor, i.e. a movable line underneath any one character on the display screen, and a facility for highlighting special fields or groups of characters, e.g. dual intensity, inverse video, were also specified.

(b) A processing unit to control system functions and to provide monitoring and scheduling of system activities.

(c) Storage for programs and formats in non-volatile but alterable form which would provide security against mains supply failure.

(d) Connection of up to eight duplex communication channels with a capability of operation at 50, 75 and 100 bits/second using ITA2 asynchronous signals.

(e) Expansion capability to include attachment of additional VDUs and the operation of communication lines at higher speeds and the use of other line protocols. Another desirable function included in the specification was the ability of the equipment to be used for ancillary purposes such as simulation of a remote job entry (RJE) terminal, and the possibility of use in a stand-alone mode for mathematical operations.

(f) A facility enabling development of programs by Meteorological Office personnel and the addition of such programs to the delivered system, was also required.

3. Description of the system

(a) (Hardware). The equipment which will be provided in response to the above requirement consists of a minicomputer housed in one pedestal of a standard office desk on which stands a Visual Display Unit and keyboard which are used to control operation of the system. (See Plate I.)

The minicomputer has a micro-processor based Central Processing Unit, 32 K of semiconductor main memory, VDU controller, floppy disc controller, communication multiplexer, and line termination cards. These functional units are linked by a multiple path 'bus' connector. These modules are similar to those used in the Sperry proprietary 'SCAMP' distributed message switching system.

(b) The Central Processing Unit is based on a Digital Equipment Corporation micro-processor LSI/11/2.

(c) The main memory consists of 32 K 16-bit words of MOS semiconductor memory with a cycle time of 300 nanoseconds.

(d) The floppy disc backing storage system is based on a flexible replaceable magnetic disc such as those in common use on small data-entry systems.

(e) A teleprinter will normally be connected to provide hard copy.

To face page 78

Photograph by courtesy of Sperry Rand Ltd

Plate I. The Meteorological Office data preparation and telecommunication terminal 'AUTOPREP' (see page 77).

Plate II. L. G. Groves Memorial Prize and Award winners with Lt.-Col. J. Groves and Mrs Groves.
Seated with Lt.-Col. J. Groves, M.C. and Mrs Groves are, left, Air Marshal Sir John Nicholls, K.C.B., C.B.E., D.F.C., A.F.C., and right, Air Commodore K. W. Hayr, C.B.E., A.F.C. Standing, left to right, are Flight Lieutenant J. A. Cowan, Sergeant R. T. Guy, Dr A. F. Tuck, Mr D. B. Hatton, and Mr F. P. Sims. (See page 92.)

Plate III. Dr A. F. Tuck being congratulated by Lt.-Col. J. Groves. (See page 92.)

To face page 79

Plate IV. Mr D. B. Hatton receiving a Cumbria Crystal ship's decanter. (See page 93.)

Plate V. Mr F. P. Sims receiving a brass carriage clock. (See page 93.)

(f) A special socket on the equipment rack enables the VDU to access a separate Read Only Memory (ROM) module which provides programs to aid the diagnosis of equipment or software faults.

(g) On the right-hand pedestal there will be space for Post Office equipment which will connect the AUTOPREP and Post Office lines.

4. System facilities

(a) *The operator–machine interface.* The programs for the running of AUTOPREP reside on the floppy disc. On switching on the system these will be loaded automatically into the main store of the processing unit. This initialization process involves self-checking by the system and on completion an indication will be given of the system state. The system clock will be brought up to the actual time by the operator.

Control of the system is effected through the VDU keyboard. A number of commands will be provided to select data or forms, to edit the information displayed, to 'page' through any data more than 20 lines long, to set the system clock, etc. The screen display includes 4 lines which are reserved to display current time of day, the last command entered, the current command, and a line reserved for error reports generated by the system. These latter reports will indicate entry of invalid commands or system malfunctions.

In the first instance maintenance and repair facilities are to be provided by the manufacturer.

(b) *Collection of observations.* Present arrangements at Collecting Centres for the collection of observations include the use of Post Office Conference Units which direct information received from a number of outstations to a single teleprinter in the Collecting Centre communication room. There are often three or four such units at a typical Centre and in order to collate and transmit these reports to Bracknell, page copy from the Conference printers is inspected, the reports are separated and sorted, and paper tapes are prepared with the data re-ordered into appropriate bulletins. The tapes are transmitted to Bracknell and other recipients via a Post Office Broadcast Unit.

An AUTOPREP installation will retain the Conference and Broadcast Units and the *modus operandi* will be analogous to the present-day method just described but much faster.

Inputs will be received from the Conference Units into 'pigeonholes', i.e. specific areas of semi-conductor main storage, within the system, from which they are available on request for display on the VDU screen.

By use of the console keyboard, reports can be displayed for identification, checking and editing. On completion of these actions a keyboard command for transmission will cause the system to compile the required bulletin, add the necessary heading and ending patterns, and transmit messages to the Broadcast Unit. Copy of all input and output data will be directed to a local teleprinter for monitoring. Identification of various data types, i.e. rainfall, CLIMAT, etc. within reports from stations will require insertion of two or three identifiers which will uniquely define the data to the processing system. However, if these characters are included with the received reports from the reporting outstations, operation of AUTOPREP at the Collecting Centre is reduced to inspection and editing of any obvious meteorological errors. Messages can then be compiled and transmitted by the system automatically at pre-defined times.

(c) *Preparation for forecast and warning messages.* At most Centres a number of messages consist of actual or forecast data added to a variety of standard forms. Tapes are prepared of these messages for later transmission through the Meteorological Office teleprinter network or over PO telex lines. The VDU terminals on the AUTOPREP system will provide an alternative method of preparation of these data.

The floppy disc system provides storage for up to 50 different forms, and operators will be able to select, by use of the keyboard, the required form, type in the forecast or other variable data, and place the completed message in a queue for transmission. The editing facilities of the VDU keyboard can be used to ensure preparation of 'clean' messages. Local copy outputs will include time of issue or receipt added automatically by the system, which includes a clock. The automatic telex facility will include dialling, recognition of 'Answerbacks', and transmission of the message. Several attempts will be made if necessary to dial each of the telex numbers included on any list related to particular forms. Incoming data from the telex system will be directed to the local copy teleprinter. In the event of two messages being received simultaneously one will be stored and 'queued' for eventual output.

(d) *Specification of formats.* A special 'off-line' program which is not normally in use, will be used to enable changes or additions to the formats held in the system. Facilities for changing lists of telex addresses and for changing of time-activated tasks will also be provided.

(e) *Diagnostics.* The processor unit and other boards housed in the equipment rack include indicator lights which can be used to help diagnose any equipment errors which may occur. A special floppy disc with diagnostic programs will probably be provided to assist operators and engineers to locate equipment faults.

5. Implementation and future developments

The first terminal which will become available as the result of this contract will be delivered to the Telecommunications Centre at Bracknell. It will be used initially to ensure that the services provided by the system meet the requirement specified by the Meteorological Office. Following acceptance it will be available for the training of selected staff from each Regional Collecting Centre for a short period just before delivery of an AUTOPREP system at their station and may be used as a local data entry terminal for AUTOCOM. An installation team from the manufacturing organization will deliver each terminal to its site and will be accompanied by representatives of the Telecommunications Branch to assist with the introduction of the system into its operational role.

The equipment delivered to all sites will be designed to fulfil the functions described above but is clearly capable of supporting other tasks. The system at Bracknell will be provided with additional peripheral equipment which can be used to develop new programs for any special outstation requirements. A support team in the Telecommunications Branch will be available to write programs which could provide useful facilities at any Centre, and will also be able to assist with any problems which may arise.

6. Conclusions

The AUTOPREP data preparation and telecommunication terminal described above is intended to help to improve the quality and punctuality of receipt of observational data which is so important for the operation of the United Kingdom automated telecommunication system. Simplification of other data preparation tasks will also be provided.

When the complete AUTOPREP network is fully operational and has achieved its design expectations in respect of improvement in punctuality and accuracy of reports, further exploitation of these modern data entry techniques in the U.K. Meteorological Office outfield may be expected.

551.525.4

The effects of altitude on soil temperature

By F. H. W. Green and R. J. Harding

(Department of Agricultural Science, University of Oxford)

Summary

It has been widely thought that, in studying seasonal soil temperatures, it is difficult to separate the meteorological effects from the effects of the physical characteristics of the soil. In this paper it is demonstrated that, at least in Great Britain, the latter are quite subsidiary to the former. A second difficulty has existed through the majority of the available soil temperature records being at the fixed hour of 0900 GMT; it is shown how careful consideration of the limited continuous observations available can, to some extent, surmount this second difficulty.

Finally, it is shown that, while in the summer there is a large decrease of soil temperature with altitude (considerably larger than that of air temperature), in the winter the decrease with altitude is small, or sometimes negative, much smaller than that of air temperature. Possible explanations of this interesting effect are considered.

Introduction

On a global scale the atmospheric climate determines the major soil groupings, such as podsols, brown earths, etc., but on a more local scale the parent rock imposes very considerable modifications on the properties of the soil. Soil climate, and in particular soil temperature, is affected by both the climate above and the physical properties of the soil, such as thermal diffusivity and capacity; thus in some aspects soil climate is spatially more variable than that of the atmosphere. This is a particular problem in the comparison of upland and lowland soil temperatures, because frequently there are large changes of soil type with altitude; but only in some respects do the soil characteristics play an important role, and many workers, such as Mochlinski (1970) and Gloyne (1971), have been able to demonstrate coherent patterns of soil temperature variation across the British Isles which are independent of the soil properties.

The thermal regime within the soil is affected by many factors including the type of air mass above the soil, the radiation received at the surface, the nature of the surface and the soil type. Of the incoming solar radiation approximately 25 per cent is reflected and a further 30 per cent is lost as net long-wave radiation; the residual, the net radiation, is partitioned into fluxes of heat and water vapour into the atmosphere, and a heat flux into the soil. The flow of heat into the soil will depend on the temperature contrast between the soil and the ground surface; the fluxes into the atmosphere will depend not only on the temperature and humidity structure in the lower atmosphere but also on the water availability at the surface (determined by the soil type, the vegetation type and the rainfall regime). The flows of energy into both the soil and the atmosphere will increase with increasing surface temperature; for a given radiation input the surface temperature will adjust until the sum of all fluxes equals the incoming energy.

Provided that the physical properties of the soil are known, it is possible, using diffusion equations, to extrapolate to all depths the diurnal and annual temperature cycles at the surface (or any particular depth). Unfortunately, the amplitude of the diurnal variation in surface temperature is dependent on the physical properties of the soil and the exchanges with the atmosphere. Using a very simple parametrization of the atmospheric fluxes Van Wijk and De Vries (1966) were able to calculate the effects of soil properties on the amplitudes of the cycles of soil temperature. While these are only rough calculations the results are both physically reasonable and can be supported by observations.

One important result is that the effects of differences on physical characteristics of the soil increase as the period under study decreases. Van Wijk and De Vries calculated the temperature regimes in peat and in sand, two soils with very different thermal characteristics; it was found that the amplitude of the annual wave of surface temperature was only 10 per cent less in sand than in peat, but for the diurnal wave the amplitude was considerably reduced in the sand (by 40 per cent). In addition the transmission of the diurnal wave through the soil is considerably different in the two soils (but again at shallow depths the annual wave is little affected). Thus, for true mean daily temperature the differences between the monthly (or seasonal) averages in different soils will be small at all depths (probably less than 1 °C). The differences at a fixed time in the day can be appreciable, but only at shallow depths; at a depth of 30 cm the amplitude of the diurnal wave is negligible in peat, and in sand is only 10 per cent of that observed at the surface. Thus at 30 cm, and below, the maximum temperature difference between the two soils is unlikely to be greater than 1 °C.

In studies of the atmospheric boundary layer Belasco (1952) and, among more recent authors, Carson (1973) and Harding (1976), have shown that in the lowest kilometre of the atmosphere lapse rates of temperature develop which are characteristic of a particular air mass, and can be broadly explained by the recent history of that air mass. Recent work (Harding, 1979a) has strongly suggested that the observed decrease of screen-level temperature with altitude (the altitudinal gradient) is highly correlated with lapse rates in the free atmosphere but modified to some extent by the energy exchanges at the surface and the atmospheric circulations over the upland. It might have been expected that interaction with the surface would totally dominate the altitudinal gradient of soil temperature, but Gloyne (1971) has shown that a gradient of the annual mean was reasonably well defined. Additionally it has been seen in the previous paragraph that the effects of the spatial variation of the soil characteristics are probably less than 1 °C for the seasonal means of mean temperature. Such a variation of temperature is small compared with the observed changes of temperature with altitude, and thus altitudinal gradients of the seasonal mean of soil temperature would be expected to be well defined.

The observations

Of the 569 reporting climatological stations within the U.K., 182 made an 0900 GMT observation of soil* temperature (sT_9). Of these there are only seven above 300 m, and there are currently (1978) only two above 400 m. Many of these stations take observations at more than one depth; agro-met stations (in particular) generally make observations at 10, 20, 30, and 100 (formerly 122) cm, although only those at 30 and 100 cm are published in the *Monthly Weather Report*. In addition there are a number of upland observations which, because of their short duration or non-standard nature, have not been archived by the Meteorological Office. These include the observations described by Oliver (1961) and Harrison (1975), but considered below are additional sets of analyses which have never been published.

There have been published very few studies of upland soil temperature. Oliver (1961) made extensive observations in upland peat in South Wales, but because observations were made only at one altitude no estimate of the elevation component can be made from these observations. Harrison (1975) made observations of maximum and minimum temperatures at 5 and 10 cm, for 21 months at two altitudes, at a site in the Dyfi estuary (altitude 3 m) and on the west side of the Plynlimon Range (altitude

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* The Meteorological Office usage is to reserve the term 'soil temperature' for depths down to 20 cm, the term 'earth temperature' being used for greater depths than this. But for the purposes of this paper, it was felt better to use the former term throughout.

450 m). These observations demonstrate a number of interesting features, one of the more striking of which is a large seasonal variation in the difference in the maximum temperature between the two sites. This variation Harrison attributes to the effects of solar radiation and soil moisture.

Gloyne (1971) investigated the altitudinal variation of the annual mean of sT_9 soil temperature and found an altitudinal gradient which was similar to that of mean air temperature but had a slight east–west variation across the British Isles. The 0900 GMT observation roughly corresponds to the daily minimum and thus will underestimate the mean soil temperature by an amount which will depend on the amplitude of the diurnal temperature wave. Because the true mean soil temperature is invariable with depth the mean annual sT_9 will increase with depth; Gloyne was able to make a simple, and accurate, correction to the 0900 observation and so use the whole network of climatological observations. Unfortunately such an adjustment is not possible if the seasonal variation of soil temperature is to be investigated. In the analysis that follows records of daily maximum, minimum and 0900 soil temperature from three stations in mid-Wales are used to identify the effects of using an 0900 observation to calculate altitudinal gradients of mean soil temperature. The identification of these effects allows the 0900 observations to be used in other upland areas of the U.K.

For the last 10 years the Welsh Plant Breeding Station (WPBS) has made observations at three sites of soil temperature at 10 cm, using mercury-in-steel thermographs. These sites are: Gogerddan, altitude 30 m and 4 km from the coast; Syfydrin, altitude 335 m and 14 km from the coast; and Pant-y-dwr, altitude 305 m and 43 km from the coast. The daily maxima and minima are available from these records and Figure 1 shows the differences between the lower station and the two high stations. Although there are minor differences between the two pairs, both show a very striking seasonal variation; for the maximum temperature the difference ranges from 1·0 °C in the winter to 6 °C in the summer, for the minimum from 0 °C to 4 °C. This seasonal variation of the gradient between the pairs of stations is very similar to that observed by Harrison (1975) between his high-level and low-level sites—although he found this pattern only for maximum temperatures—and also by Smith (1976) for the Pennines and North Wales.

These observed differences in soil temperature could be due to a number of factors, the most obvious of which is altitude, but it is also possible that the differences in soil types and the increased distance inland of the higher stations may be important. It is also important to establish whether this effect is confined to mid-Wales or is a feature of soil temperatures in all upland areas of the British Isles. To investigate these points use has to be made of the only other upland observations available, those taken at 0900 GMT at climatological stations. It can be seen from Figure 1 that the differences between the 0900 observations at the WPBS sites are, as expected, close to those of minimum temperature, and the altitudinal gradients of the 0900 observations will show the characteristic patterns of the mean. The three climatological stations above 400 m for which observations of soil temperatures are, or have been, published in the *Monthly Weather Report* of the Meteorological Office are:

MOOR HOUSE, Cumbria	556 m, 1957–	30 cm
WIDDYBANK FELL, Co. Durham	508 m, 1968–	10 cm, 20 cm, 30 cm
ONECOTE, Staffs.	411 m, 1959–68	30 cm and 120 cm

When compared with those at their nearest available lowland climatological stations, the observations at these sites show that the distinctive seasonal pattern observed in Wales is also characteristic

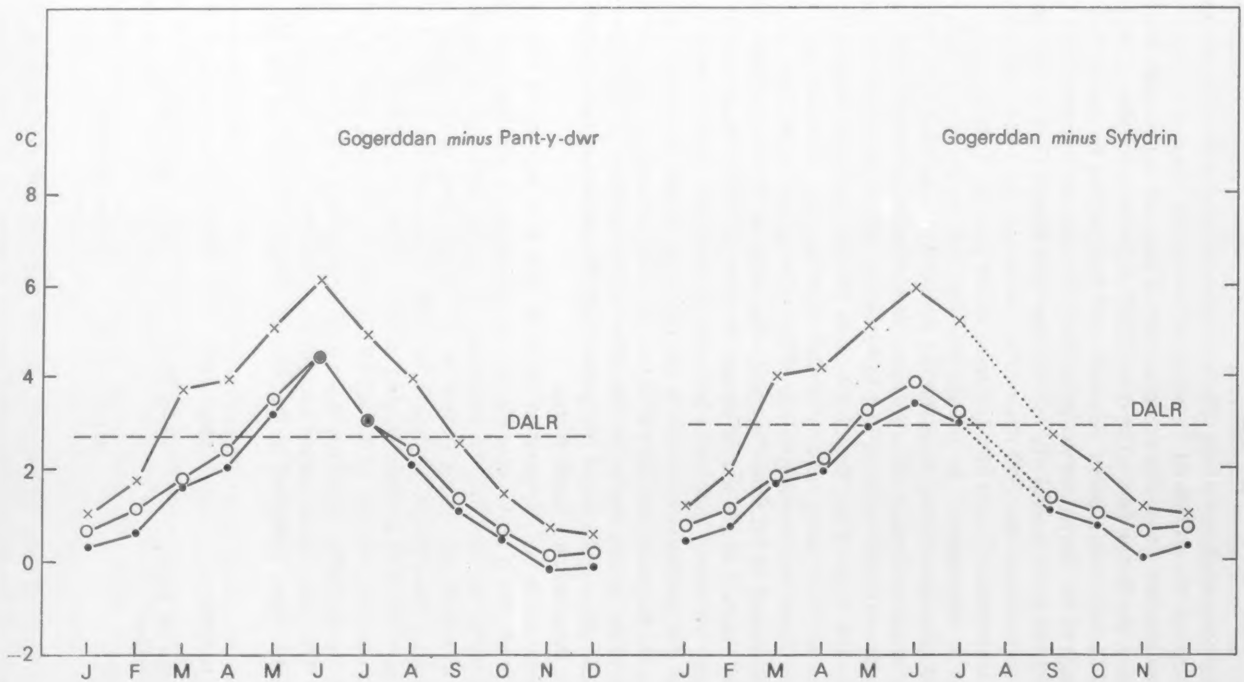

Figure 1. The differences between maximum (×), minimum (·) and 0900 GMT (○) 10 cm soil temperatures recorded at a low-level station, Gogerddan (alt. 30 metres), and two high-level stations, Pant-y-dwr (alt. 305 metres) and Syfydrin (alt. 335 metres) in mid-Wales (1967–72). The dashed lines marked 'DALR' indicate temperature differences consistent with the dry adiabatic lapse rate.

of the Pennines (Figure 2). The Onecote observations also demonstrate that the pattern extends to a depth of 120 cm, with no sign of diminution, and is probably a feature of the entire temperature profile in the soil. The lowland stations used in the Pennine comparison are well away from coastal influences, indicating that the pattern observed is solely an effect of altitude.

The two upland stations of Widdybank Fell and Moor House have very different soil types; Moor House has a peaty clay and Widdybank Fell an alkaline soil with a small organic content and thus these are two extremes of thermal diffusivity. As the stations are only 7·5 km apart and have similar exposures, the differences between them show the effects of two very different soils on the seasonal pattern of the sT_9. In the summer the peaty clay is $\frac{1}{2}$ °C warmer, which is consistent with the differences calculated earlier; it is also confirmation that for the seasonal variation the effects of the differences of soil properties are secondary to those of altitude.

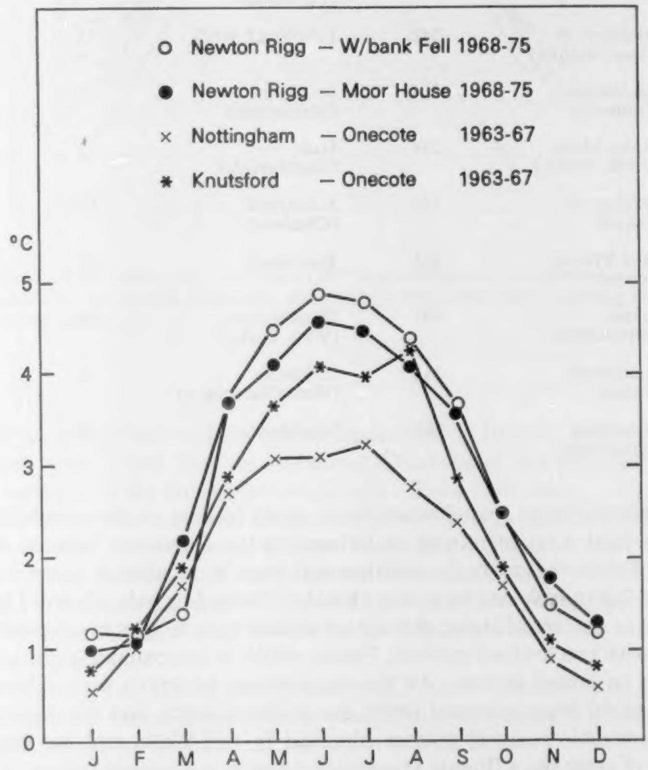

Figure 2. The differences between the mean 0900 GMT (30 centimetre) soil temperature observations for four upland/lowland pairs of stations in, and around, the Pennines.

Other upland observations

Unfortunately there are in Britain, outside the Pennine area, no climatological observations of soil temperature above 400 m. There are, however, a number of stations between the altitudes of 400 m and 200 m and it is possible to identify a number of upland/lowland pairs for which the altitude differences are greater than 200 m (Table I and Figure 3). These data need to be regarded with some care because the temperature differences due to altitude will be of a similar order to differences which might arise because of variations in soil type.

Table I. *The available upland/lowland pairs with an altitude difference greater than* 200 *metres*

No.	Upland station	Altitude *metres*	Lowland station	Altitude *metres*	Altitude difference *metres*
1	Achnagoichan (Inverness-shire)	305	Forres (Morayshire)	50	255
2	Achnagoichan	305	Faskally (Perthshire)	94	211
3	Eskdalemuir (Dumfriesshire)	242	Edinburgh RBG	26	216
4	Spadeadam (Cumbria)	274	Southport (Merseyside)	5	269
5	Silpho Moor (North Yorks.)	203	Hull (Humberside)	2	201
6	Bwlchgwyn (Clwyd)	386	Knutsford (Cheshire)	65	321
7	Lake Vyrnwy (Powys)	303	Knutsford	65	238
8	Buxton (Derbyshire)	307	Huddersfield (West Yorks.)	99	208
9	Crumbland (Gwent)	345	Swansea (West Glamorgan)	8	337
10	Helmshore (Lancashire)	261	Southport	5	256

In some cases there are large spatial separations, again leading to the possibility that influences other than the altitudinal component may be influencing the differences between the stations. The pairs listed in Table I were chosen by the criterion that there be an altitude range in excess of 200 m. Three stations above 200 m have not been used (Kielder Castle, Loggerheads and Llandrindod Wells) because they are near to stations of higher altitude which have already been investigated. Achnagoichan has been compared with two lowland stations, Forres, which is approximately one kilometre from the coast, and Faskally, an inland station. All the observations are taken from *Climatological Memorandum* 77 of the (British) Meteorological Office, are at 30 cm depth, and are corrected to the period 1961–70. The characteristic seasonal pattern observed in mid-Wales and the Pennines is evident between all but one of these pairs (Figure 3) suggesting that it is a general feature of upland areas in the U.K. The exception to this general picture is the Buxton/Huddersfield pair, but Buxton/Knutsford is similar to the other pairs and so it is the lower site, at Huddersfield, which is exceptional.

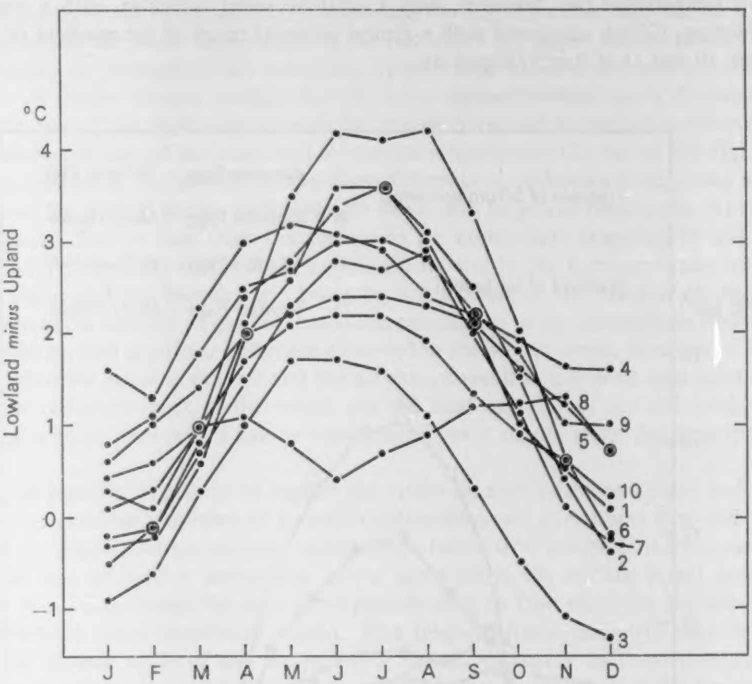

Figure 3. The differences of the mean (1961–70) 0900 GMT 30 centimetre soil temperatures between the 10 available upland/lowland pairs with an altitude separation greater than 200 metres (not including those described earlier). For details of the pairs see Table I.

Table I contains no sites in the southern half of England, or in Ireland; there are, however, pairs of stations within these areas which have an altitudinal difference of less than 200 m but still show a marked seasonal variation of the altitudinal component. These pairs are:

(a) Two stations at the top and bottom of the Chiltern Escarpment, within the Aston Rowant National Nature Reserve, which were operating between 1966 and 1971; they have an altitudinal difference of only 94 m but they are less than one kilometre apart and have very similar chalk soils.

(b) Yarner Wood (195 m) and Starcross (9 m), two stations south-east of Dartmoor, Yarner Wood being a standard climatological station, run by the Nature Conservancy and South West Water Authority since 1966.

(c) Lislap Forest (Co. Tyrone, 175 m) and Moneydig (Co. Londonderry, 34 m) in Northern Ireland.

It thus appears that this seasonal variation is evident over the entire U.K., is independent of soil properties and exposure of the sites, and extends up to at least 550 m.

Comparison with air temperature

The annual mean altitudinal gradients of air and soil temperature are similar (Gloyne, 1971). The

gradient of air temperature has, however, only a small seasonal variation, with a typical range of 2 °C km^{-1} (Harding, 1979a), compared with a typical seasonal range of the gradient of soil temperature of between 10 and 11 °C km^{-1} (Figure 4).

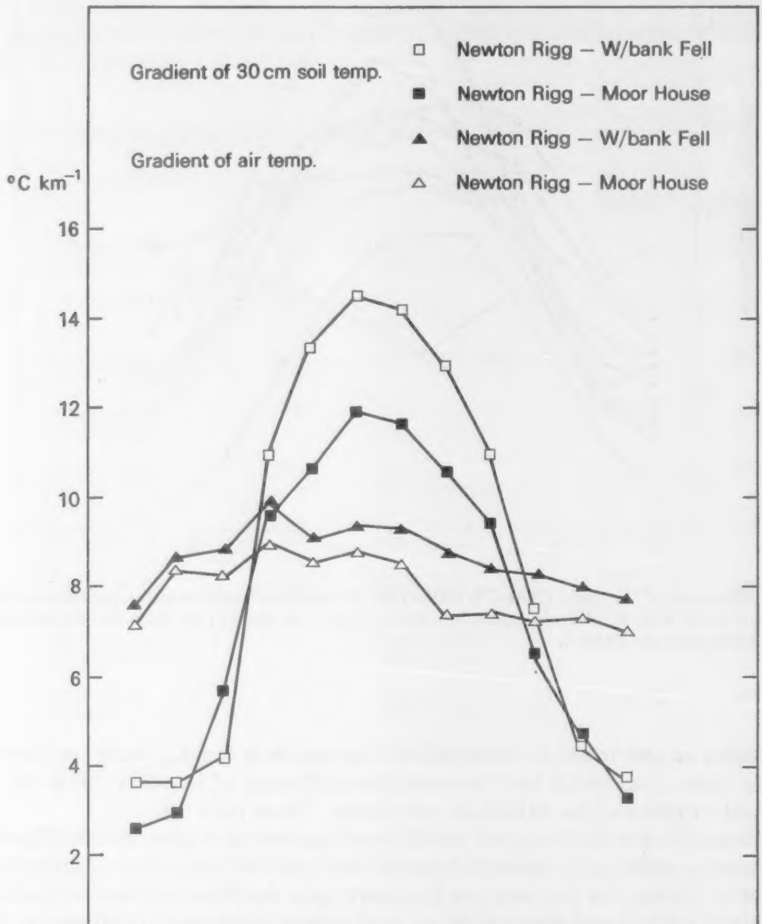

Figure 4. The altitudinal gradients of air and soil temperatures between the two high-level stations in the Pennines and a representative lowland station (Newton Rigg, alt. 171 metres, 1968–75).

One interesting consequence of the differing seasonal cycles of the altitudinal gradients is that the differences between the temperature in the air and that in the soil vary with altitude. Figure 5(a)

illustrates this point; at the lower station (Gogerddan) the soil is warmer than the air in the summer and at approximately the same temperature in the winter; at the upper station (Pant-y-dwr) the soil is warmer than the air throughout the year, and, significantly, between one and two degrees warmer in the winter. A similar picture emerges for the other upland/lowland pairs discussed previously, although in the case of the 0900 observations the observed air–soil temperature difference is complicated by the underestimate of the mean soil temperature in summer (by use of the sT_9).

The lowland pattern of the air–soil temperature difference is understandable, being almost zero in the winter, when the surface energy exchanges are small, and large and negative in the summer, when there is a large net flow of heat from the surface to the atmosphere (supplied by the net radiation input). The lower magnitude of the difference in the upland in the summer is also understandable, the radiation input and the Bowen ratio being probably lower in the summer (in the upland) and thus a reduction in the transfer of sensible heat from the surface to the atmosphere would be expected. The relatively large, and negative, difference observed in the winter poses, however, a problem. The temperature difference between the soil and the air cannot result in a flow of heat from the soil, since neither the low radiation input in the winter nor the heat capacity of the soil could maintain the upward flux of sensible heat which can be calculated from a simple mean flux/gradient relationship (Figure 5(b)).

While it is not possible at present to explain the relatively high observed upland soil temperatures, it is instructive to consider a number of possible explanations and to examine their deficiencies. Even in the upland the winter soil temperature rarely drops below 0 °C although it frequently approaches this value, and thus at least a proportion of the moisture in the surface layers must be freezing regularly, but remaining frozen for only short periods of time (too short for the sub-zero temperatures to penetrate to the measurement depth). This frequent freeze/thaw will tend to moderate the extremes of the diurnal cycle of soil temperature; thus if this were an important mechanism, the upland minima would be increased and the maxima decreased, relative to both the air temperature and the lowland soil temperature; this is not what is observed, the mid-Wales observations showing increased maxima and minima. Snow would similarly moderate the diurnal extremes rather than elevate both the maxima and the minima.

A further possible influence is the effects of the variations, both spatial and temporal, of soil moisture; in the summer the upland soil will be wetter than the lowland, and this will lead to increased evaporation and a larger thermal diffusivity of the soil in the upland, which may well explain the relatively low soil temperatures observed in the summer. In the winter, however, there is little difference in the soil moisture between the upland and lowland; in addition the radiation levels are low and therefore the temperature of the soil should be similar to that of the air.

It must be expected that the cause of the anomalously high upland soil temperatures lies in the energy exchanges in these areas; it is not possible to model these exchanges simply, but the observations of soil temperature presented above do indicate that the transfers of heat, water vapour, and radiation are very different in upland areas from those encountered in the lowlands.

Conclusion

It has been demonstrated that in the winter there is very little change of soil temperature with altitude but in the summer the decrease with altitude is large, considerably larger than that of the air temperature. Although the relatively high upland soil temperatures in the winter result from only a small amount of additional heat storage in the soil, the maintenance of a high soil temperature, relative to the air, requires a large input of energy, additional to that provided by radiation, or a suppression of the heat exchange between the soil and the air. The physical mechanism behind this

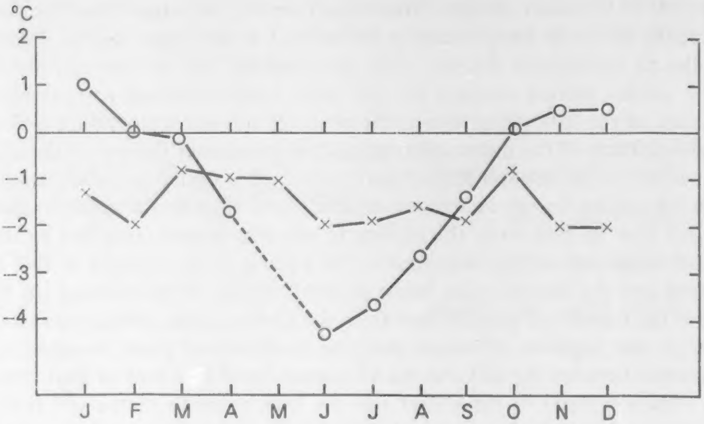

Figure 5(a). The differences between mean daily air temperature and mean daily (10 centimetre) soil temperature for Gogerddan (○) and Pant-y-dwr (×).

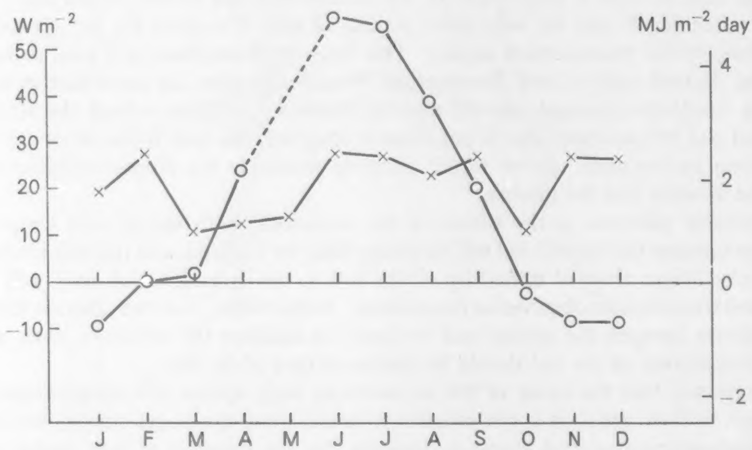

Figure 5(b). The mean, upward heat fluxes calculated from the differences shown in Figure 5(a) using a simple flux/gradient relationship: Gogderddan (○); Pant-y-dwr (×).

behaviour of soil temperature cannot at present be explained; there can be no doubt, however, that a large seasonal variation of the altitudinal gradient of soil temperature is observed in every upland area of the British Isles (and is also observable in other parts of western Europe), independent of soil type or exposure.

The characteristic pattern of soil temperature in upland regions must have important consequences for the productivity and survival of upland plant and animal communities. There is considerable evidence to suggest that many plant physiological processes are more dependent on the temperature of the soil than on that of the air (Alcock *et al.*, 1968) and further, that temperature, along with wind speed, is the major constraint on ecological productivity in upland regions (Harding, 1979b). The prediction of relatively high winter, and low summer, upland temperatures is obviously an important aspect of the assessment of this productivity.

Acknowledgements

We thank the Director of the Welsh Plant Breeding Station for permission to use their observations, and the staff of the Institute of Hydrology, Wallingford, and the Department of Agricultural Science, University of Oxford for many helpful discussions. This work is part of a study of upland climate supported by the Natural Environment Research Council.

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AWARDS

L. G. Groves Memorial Prizes and Awards

The annual award of prizes took place on Friday 24 November 1978 at the Main Building, Ministry of Defence, Whitehall (see Plates II–V). For the first time since the awards were instituted—the first were made in 1947—Major and Mrs K. G. Groves were unable to be present at the ceremony; Major Groves's nephew, Lt.-Col. J. Groves, M.C., who was accompanied by his wife, took the place of his uncle and presented the prizes. The Air Member for Supply and Organization and Vice Chief of the Air Staff designate, Air Marshal Sir John Nicholls, K.C.B., C.B.E., D.F.C., A.F.C., presided.

In his introductory remarks Lt.-Col. Groves explained that his aunt had most unfortunately broken a leg a few weeks before, but that she was making good progress and both she and Major Groves intended to be present at the 1979 prize-giving. Lt.-Col. Groves gave an entertaining account of his own rather negative contribution to aircraft safety in the 1930s when he was a subaltern; while on a liaison flight with the Royal Air Force he forgot to remove his spurs, with consequences that were unfortunate and might have been quite unpleasant!

The 1978 Aircraft Safety Prize was awarded jointly to Flight Lieutenant J. A. Cowan of Royal Air Force Kinloss and Sergeant R. T. Guy of Royal Air Force Cosford for their work in the design and manufacture of an Emergency Locator Transmitter Homer with the following citation:

'The difficult task of locating persons who have abandoned ships or aircraft can be simplified if the survivor uses an Emergency Locator Transmitter (ELT) and the rescue force are equipped with a suitable homer. The success of the ELT in aviation has led to its carriage in ships of the merchant fleet. ELT homers are carried by military aircraft and by a small number of military rescue boats assigned to search and rescue duties. However, there have been occasions when a VHF signal from a civilian ELT has been intercepted but rescue has been delayed because the U.K. military search and rescue forces can only home on to UHF transmissions. This time-consuming and potentially dangerous situation could be reduced if ships of the merchant fleet were fitted with a suitable homer. This fitment would also help military search and rescue forces from being over-burdened because of their unique homing capability. To this end Flight Lieutenant Cowan and Sergeant Guy have designed an effective but inexpensive homing aid—known as 'The Brawdy Homer'—which provides homing indications on VHF or UHF transmitter signals. The introduction of their homer to merchant ships, particularly those assigned to search and rescue duties, would permit them to home on to all Emergency Locator Transmitters in current service.'

The 1978 Meteorology Prize was awarded to Dr A. F. Tuck of the Meteorological Office with the following citation:

'The Meteorology Prize is awarded to Dr A. F. Tuck for his contributions to our understanding of the complexities of the interaction of atmospheric chemistry and dynamics in controlling the amount of ozone in the atmosphere. His work has helped in the appreciation of the limitations of current numerical techniques in assessing possible changes in the total ozone caused by man's injection into the atmosphere of pollutants such as nitrogen oxides or fluorocarbons. In addition, he and his colleagues under his leadership have made important suggestions about possible interaction between the atmospheric carbon dioxide amounts and the ozone chemistry.'

The 1978 Meteorological Observer's Award was awarded to Mr D. B. Hatton of the Meteorological Research Flight, Royal Aircraft Establishment, Farnborough, with the following citation:

'Mr Hatton joined the Meteorological Research Flight in 1970 and, in addition to carrying out his main task of instrument maintenance and development, soon became a recognized observer in the Varsity and Canberra aircraft. In 1974, with the arrival of the Hercules, he rapidly became the senior flight leader in this aircraft, later also becoming one of the team of aircraft scientists. His competence in these tasks and his calm, dedicated manner earned him the respect of all members of flight and indeed he became accepted by the aircrew as being a completely integrated member of the Canberra team. His knowledge of the relevant instrumentation and his expertise in the air have, throughout the past six years, contributed significantly to the advancement of many of the Meteorological Research Flight projects.'

The 1978 Second Memorial Award was awarded to Mr F. P. Sims of the Meteorological Office, Akrotiri with the following citation:

'In 1976, some 37 years after beginning his career with the Meteorological Office, Mr Sims was appointed to the post of Principal Meteorological Officer at Royal Air Force Akrotiri, where he is still serving. In an aircraft accident early on the morning of 7 December 1977 the Main Meteorological Office at Akrotiri was totally destroyed. Five of the seven staff on duty were killed and two were severely burned. Mr Sims showed outstanding qualities of initiative and resourcefulness in re-establishing full meteorological services at Akrotiri within 24 hours, making a major contribution to flight safety in the disturbed weather of the winter season in Cyprus. In addition, the involvement of Mr Sims with the families directly affected by the accident was marked by a sensitivity and humanity which helped to share some of the burden of the personal tragedies of Cypriots and British alike.'

Reviews

Methods in Computational Physics, Volume 17, General Circulation Models of the Atmosphere, edited by Julius Chang. 230 mm × 155 mm, pp. x + 337, *illus.* Academic Press Inc., Publishers, New York, 1977. Price US $35.50.

Understanding climate and its variations, and authoritative assessment of the risks of climatic change, are clearly going to provide massive problems for meteorologists for many years to come. Though the attack on the climate problem will have many prongs, it is the general circulation models (GCMs) which will provide the heavy artillery. The appearance of this major new work is very timely, and especially welcome in that it concentrates on the practical problems which modellers encounter.

The book comprises five articles. The first by Kasahara on general computational aspects of numerical models contains much of interest to modellers themselves as well as providing also a very useful introduction to the whole subject for newcomers. Though the science abounds with difficulties it is the most obvious ones which are most intractable. The problem of choosing a grid array on a spherical earth was one of the earliest to be recognized when global models were formulated and nothing wholly satisfactory has yet emerged—the polar regions require some sort of special treatment. Again the vertical coordinate may be specified in different ways, by height, pressure, potential temperature and others, each with their drawbacks. The most widely favoured, the sigma coordinate

system, sidesteps a problem at the lower boundary, yet modifications have to be introduced over mountainous regions. The effects of orography are still not properly introduced into model formulation. Again we have the upper boundary problem, some theoreticians claiming that its formulation is crucial, and modellers on the other hand finding crude assumptions satisfactory—indeed deriving surprisingly little benefit from improved vertical resolution. Arakawa is well worth reading on these problems. On differencing schemes, an area in which he has published his best-known work, I found him disappointing and hard to follow in parts, but on the difficult concept of non-linear instability his brief discussion is very illuminating.

The book continues with detailed descriptions of the formulation of four GCMs by groups at the National Center for Atmospheric Research (NCAR), Boulder, Colorado, the University of California at Los Angeles (UCLA), the Meteorological Office, and the Australian Numerical Meteorology Research Centre. While the UCLA model description is confined to the design of dynamical processes—and goes into great detail for instance on model energetics—the NCAR and U.K. groups include in their contributions the detailed formulation of physical processes. These processes, in many respects imperfectly understood and defying precise specification, lie at the heart of the modelling problem, and years of painstaking research into methods of incorporating them lie ahead. The inclusion of solar and terrestrial radiation poses severe difficulties, particularly the role of clouds in the radiation budget. One process which does not appear at all in the present version of any model in this book, though some groups such as the Geophysical Fluid Dynamics Laboratory (GFDL) of NOAA, U.S.A. are beginning to tackle it, is the interaction of atmosphere and ocean. Essential for any complete simulation of climate, the inclusion of the effects of two-way exchange of heat and momentum between sea and air adds a new dimension to the problem and calls for an interdisciplinary approach.

Special interest attaches to the final chapter contributed by the Australian group. Besides the work reported here, general circulation spectral models are employed by GFDL, while a spectral model is in operational use for short-period prediction in Canada. In this book the authors outline several important advantages accruing from the use of spectral coordinates. There are also drawbacks—apart from some practical difficulties; physical processes of course do not lend themselves to spectral treatment, while the representation of meteorological systems in a predetermined functional form may seem artificial to many meteorologists. Yet the advantages too are undeniable, real representation of a continuous fluid by continuous variables eliminating the truncation errors of grid-point schemes. The economy too is obvious—much time is wasted by grid-point models in calculating negligible changes at a succession of points, for instance in the subtropical anticyclone.

The progress made already with GCMs is remarkable. The U.K. and Australian contributors illustrate mean charts derived from long-period model runs which are seen to reproduce all the main features which go to make up the mean state of the atmosphere. Several groups have demonstrated that beginning with an atmosphere at rest and of uniform temperature it is possible to achieve integrations where the full annual climate cycle is reproduced. The next stage provides a sterner challenge still for numerical modellers. Will it also prove possible to simulate the whole range of variations of climate, and eventually provide a convincing solution to the problem of long-term climatic change?

Many scientists will be grateful that in a fast-moving subject such as this, the large number of distinguished contributors to this book have found time to pause and to assemble material available otherwise, if at all, only in widely scattered papers.

P. Graystone

Water data 1976, by the Department of the Environment, Water Data Unit, Reading, Berkshire, 295 mm × 210 mm, pp. iv + 85, *illus.*, 1978. Price £2.

Water data 1976 is the third in an annual series, intended to present summaries of the data which have been collected each year from the various branches of the Water Industry, including water abstraction, treatment and supply, hydrology, water quality, fisheries and finance.

The standard of presentation of the figures and tables is good, although there are a number of clerical errors (for example, the dates of the heavy rainfall at Spelga Dam shown in Tables 12 and 13 do not agree).

For reference purposes, the volumes in the series are likely to prove to be very important. However, people who are not closely involved with the Water Industry, but who are simply interested, will probably find them rather heavy going and may fail to accept that connecting themes or interpretation are not essential to a source book of data.

It is assumed that readers will be fully conversant with the many disciplines covered by the volume, and are therefore able to interpret the numbers for themselves and to understand their significance. In fact, most people will be familiar with only a few of the topics. A fuller explanation of each set of data and a discussion of them could have brought home to the average reader the extent of the largely unpublicized activities behind the flow of water from a household tap. Why, for example, is the average daily consumption of water 431 litres a head in Scotland but only 292 litres a head in England and Wales? The seven excellent photographs would have contributed far more to the report if they had been accompanied by an expanded text.

The interest value of this reference material, obviously prepared with great care, could have been much enhanced for the general reader by the addition of a few sentences showing the uses of the data presented and drawing attention to the important features. The famous drought of 1975–76 might have been further exploited for this purpose, and one must hope that future issues in this series may move in this direction.

C. A. Nicholass

The Guinness Book of Weather Facts and Feats, by Ingrid Holford. 235 mm × 175 mm, pp. 240, *illus*. Guinness Superlatives Ltd, Enfield, Middlesex, 1977. Price £6.50.

This is a welcome addition to popular books on meteorology and weather which will appeal both to amateur meteorologists and to professionals (many of whom will find it fascinating although at times irritating). There is an interesting amalgam of facts, feats and historical information presented in a concise form, and the introduction claims that all the recorded absolute weather extremes are listed.

There are 17 chapters, each concerned with a separate aspect of weather. Chapter 1 is entitled 'The Radiating Sun' and after considering each of the weather elements in turn the book finishes with 'Forecasting the Weather'. The chapters in between give lots of facts and feats ('feat' is used here to indicate a notable weather event) on Dew, Frost, Fog, Clouds, Rain, Flood, Drought, Snow, Hail, Atmospheric Electricity and Thunderstorms, Whirlwinds, Tornadoes and Waterspouts, and even Optical Phenomena. There is a very poorly presented Appendix of miscellaneous information (principally of some Meteorological Office services) and a good Index. Each chapter is headed with one of many stamps issued to celebrate the International Meteorological Organization–World Meteorological Organization centenary in 1973. This would have been excellent if each stamp had been pertinent to its chapter—for instance, a windfinding radar heads the chapter on 'Water'. A Tunisian stamp heading the chapter on 'Forecasting the Weather' is annotated as being the Headquarters of the World Meteorological Organization, Geneva—it is not!

Most chapters begin by introducing the subject matter, giving a little of its history—together with a mention of some of the earliest scientists involved in the field—and then record the 'feats'. The scientific descriptions are highly simplified and although usually adequate at an amateur level will often not satisfy the professional. The scientists recorded in the text belong mainly to the 17th, 18th and 19th centuries and there are occasional references to Greeks and Romans. Modern scientists are infrequently mentioned. The 'feats' of the weather cover the world, but, naturally, those of the British Isles are given much greater coverage than they warrant from a global viewpoint. One is left with the impression that most occurred either in the last 20 years or around the turn of the century. A more even time coverage would have been preferable. The book is in the style of an encyclopedia with paragraph headings in bold type followed by short descriptive text. It is usually satisfactorily written with occasional touches of humour, but is sometimes colloquial and at times confused. Chapter 17 on 'Forecasting the Weather' seems particularly bad and gives the impression of a hastily written addition with an inadequate description of current forecasting methods.

Many facts are given as positive statements (for instance on page 158 it is stated that 'Snow lies on the ground whenever air temperature is below 37 °F (3 °C)') when qualifications or generalizations are required. There are poor descriptive terms (e.g. 'light pressure winds' on page 124 and 'A ridge of high pressure is an elongated extension of isobars from an anticyclone' on page 76) and some statements which could have been expressed better (e.g. it would be more precise to say '30-day predictions from numerical models do not yet provide useful forecasts' rather than '30-day forecasts are still not possible by numerical forecasting' on page 221).

The book is full of good diagrams, some helpful charts and many photographs (which are usually excellent—although that of Arctic Sea Smoke opposite page 112 is technically poor and that on page 161 must be rather old). Many of the tables are good but those with their title at right angles to the contents (as on page 39) are irritating and some lack vital information (e.g. distance to sea is omitted from the table on page 34). It is a great pity that the diagrams etc. are not numbered and rarely mentioned in the text—such reference would simplify some sections (e.g. in the description of optical phenomena on page 202 *et seq.*). Most measurements are given in both imperial and metric units and temperatures in both Celsius and Fahrenheit. This is inevitable at the present time, but is it really necessary to devote most of pages 22, 23 and 27 to explaining and illustrating the temperature conversion process?

There are few references to other works and a Bibliography which included original data sources—particularly of climatological information—would have doubled the value of the book. There is irrelevant information (e.g. a photograph of the harbour at St Tropez 'warming in the sun' opposite page 48 and a comment on motorway lights being left on for no apparent reason on page 110).

The radiosonde is perhaps the most important instrument of modern meteorology and it deserves more space than some 80 words on page 50 and further mention in a poorly written section on pages 218–219. The coverage of weather ships is minimal and meteorological satellites (although providing a few good photographs) could have been written about in more detail.

The book concludes with 'Machines may continue to provide increasing information on which forecasts can be made, but nothing is ever likely to substitute for the eyes and logical reasoning of human beings'. Who can tell how forecasting will develop? Computers have been in use for only 10 to 20 years and perhaps the 21st century will see machines which can reason even better than man!

There are many points, some of which are mentioned above, which are easy to criticize in a book of this sort, but one is attracted by the overall layout and finds much of interest. This is a book principally for browsing and it will find a welcome home among those with an existing interest in weather and those who like to ponder over facts and feats.

E. A. Spackman

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CONTENTS

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